FACILITY FORM 602
N65-29654 (ACCESSION NUMBER) (THRU)
25 (PAGES) 1 (CODE)
TMX-51962 (NASA CR OR TMX OR AD NUMBER) 14 (CATEGORY)

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OPERATION RESULTS

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Presented at the SPIE 9th Annual Technical Symposium

Miami Beach, Florida
August 24-28, 1964

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INTRODUCTION

The tracking telespectrograph, figure 1, is a precision instrument used to track the reentry flight of a space vehicle or satellite and record on film a continuous spectrum of its light output and supplementary sequential engineering data with respect to real time. This film is subsequently used to study the physical effects on the leading edge of the reentering vehicle as it passes through the denser layers of the atmosphere. The entire telespectrograph optical package is mounted on a precision, azimuth-elevation tracking mount. The instrument is controlled by one operator using an "Aided Tracking-Stiff Stick" control, or it may be slaved to external range instrumentation. In the latter event, the operator may override the external slaving signals to correct the aim of the telespectrograph.

LANGLEY REENTRY STUDIES

The Langley Research Center has been engaged in reentry experiments for a number of years. Several research vehicles are in current use, ranging from Scout boosters and small solid-fuel rockets with shaped charges, to achieve reentry velocities on the order of 20,000 feet per second, to the Fire vehicle, with an Atlas booster and an additional stage to achieve velocities in the range of 30,000 to 40,000 feet per second. Of particular interest in this series of experiments is the radiation from the air before the reentry body becomes heated

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to incandescense. To detect this radiation the largest practical collector and most sensitive detectors are needed. Since predictions vary widely as to the nature and amount of radiation to be expected, wide dynamic and spectral range are desired.

The primary purpose of the Project Fire spacecraft is to furnish much-needed data on heat phenomena at reentry speeds corresponding to escape velocity, that is, in the neighborhood of 25,000 mph. Secondary missions include the gathering of information about the plasma sheath, which causes communications blackout during reentry.

Project Fire marks the first actual reentry experience at speeds matching the velocity of future spacecraft returning from interplanetary and lunar missions, and furnished important guideposts for future space vehicle design.

The Fire spacecraft was launched from Cape Kennedy by an Atlas-D booster into the trajectory shown in figure 2. A velocity package using the Scout third-stage solid-propellant Antares II rocket motor and Scout guidance added the speed needed to drive the reentry payload back into the atmosphere at 25,000 mph. The reentry took place near Ascension Island in the South Atlantic, some 5,200 miles downrange.

Flight time was just over 32 minutes. Launch was followed by a 21-minute coasting period, during which the spacecraft reached an apogee of approximately 500 miles and the spacecraft is oriented to the correct entry attitude. Firing of the Antares II motor and payload separation began about 26 minutes after lift-off. Maximum reentry heating lasted about 42 seconds, during which time data, over 100,000 different measurements in all, were telemetered to ground stations and simultaneously stored in a tape recorder aboard the vehicle. The latter is to permit transmission of data acquired during the "blackout" period.

Data from the tape recorder were retransmitted 45 seconds after initiation of reentry when the package was past the peak-heating pulse and normal communications resumed. The vehicle itself was not recovered.

The fundamental laws of physics which produce the familiar phenomenon of a meteor streaking across the nighttime sky also impose severe conditions upon a reentering spacecraft.

Most important of these fundamentals to reentry is the principle of conservation of energy.

Applied to atmosphere entry, the principle produces a series of events in which most of the speed of the reentering vehicle (kinetic energy) is changed to heat (thermal energy). The requirement that the total energy must remain constant implies that the thermal energy produced during reentry must increase as speed increases. Hence, reentries at lunar and planetary return speeds will generate significantly higher amounts of heat, and higher heating rates, than entries at lower, orbital speeds.

Air molecules compressed ahead of the entry vehicle become hot, so hot, in fact, that several complex physical and chemical reactions occur with incredible rapidity.

These reactions are not yet fully understood, and it was the purpose of Project Fire to provide direct measurements in flight which can be used as key points against which to check theoretical studies and the data collected in laboratory experiments.

At the speed Project Fire attained, the temperature of the gases in the shock wave area just ahead of the blunt reentry body approached 20,000° F. Temperature, of course, is an indication of the energy which is being transferred from the speeding vehicle into the surrounding air. The energy transferred is sufficiently large to break diatomic gas molecules into individual atoms, and further, to ionize many atoms by temporarily changing the number of electrons they possess.

Heating during reentry is itself a complex phenomenon, possessing two primary types or modes. At satellite speeds and below, a type of heating called convective is predominant. Convective heating takes place when heat passes directly from the air to the vehicle flying through it.

At higher speeds, a second type of heating known as radiative becomes more and more important. One major goal of Project Fire was to find out exactly how important the radiative component of total heating is at 25,000 mph.

Considerable uncertainty exists in the area of estimating the relative importance of radiative versus convective heating at lunar reentry speeds. Predictions of radiative heating based on different existing theories can vary as much as tenfold.

Onboard experiments will include direct measurements of radiation from the hot gas cap by means of radiometers specially developed for Project Fire. The total amount of heating will be measured by more than 250 thermocouples.

TELESPECTROGRAPH

General

The telespectrograph consists of a precision mount, a large reflecting telescope, and a spectrograph with photographic and tape recording. The telescope spectrograph was designed and built by J. W. Fecker Division of American Optical Company, Pittsburgh, Pennsylvania, and the mount was designed and built by Naval Ordance Test Station, China Lake, California. Its costs exceed $1,000,000.

The instrument is equipped with a 36-inch aperture telescope with an f/3.0 primary. The effective focal length is 288 inches. A novel feature is use of pneumatic self-adjusting bellows to support the 500-pound mirror. The spectrograph is of unusually wide spectral and dynamic range.

Tracking Mount

The mount which is shown in figure 3 is a hydraulically driven two-axis, servo-controlled mount. The azimuth range of rotation is four turns; the operational elevation range of rotation is from -7.5° to $+90^{\circ}$.

The hydraulic power drive system provides for operating at angular velocities up to 60°/second, and at accelerations up to $180^{\circ}/\text{second}^2$. The system allows switching from remote to local control without the occasioning of any abrupt slowing or jerkiness that might cause the operator to lose track of the target in his viewing scope. The mount is driven in both azimuth and elevation by a multicable friction transmission system. This transmission system is used as the final part of the drive mechanism of the hydraulic valve control system to attain zero mechanical backlash, smooth, low-speed performance, and to prevent the transmission of any vibration to the readout equipment.

Sixty cables are utilized in the azimuth drive system, and are wrapped around the 104-inch-diameter azimuth frame. The azimuth frame, in turn, is scored about its circumference to receive the cable and to maintain a constant cable friction load about the azimuth frame. In a similar manner, the cables from each of the elevation drive capstans drive the two $49\frac{1}{2}$-inch-diameter scored wheels which are located on either side of the telescope assembly, and are attached to each of the trunnion shafts of the telescope. Equal torque between the hydraulic motors, which drive the capstans is maintained by the provision of capillary tubes connecting the motors to equalize the pressure. The servo valves are gain matched by trimming the resistors in the torque motor circuitry. The torque motors are driven in series from constant current, servo amplifier systems.

The driving input signals, either from the manual control console which is located on the mount, or from the external range instrumentation, are applied to either the elevation data gearbox assembly or the azimuth data gearbox assembly, which contain the respective synchro control transformers which provide the error output signals to the servo systems.

An electric-to-mechanical transducer is located adjacent to each of the five hydraulic torque motors. The error output signal from the servo amplifier controls the position of a pivoting arm within the transducer. The position of this pivoting arm determines the direction and pressure of the hydraulic flow to the drive torque motor.

The operator's station includes a seat, which rotates with the telespectrograph; the operator's control panel, which includes the "stiff stick" and control switches; and a 50-power 12-inch Cassegrain-type sighting scope.

The seat has an extended footrest and an adjustable headrest, and is designed so that the elevation axis of the telespectrograph passes through the operator's head at a point directly behind his ear. A switch is located on the footrest which operates the emergency stop circuitry. Chair motion is limited to a range from -5° to 45° by the telespectrograph elevation limit switches, which are set at -7.5° and 90°. In this manner, the operator can readily observe the target through his sighting scope as the telespectrograph is rotated toward the 90° position.

The operator's control panel is also mounted to the chair assembly. During operation, the control console is positioned above the operator's lap, and locked in position. It can be swung forward on a pivot to facilitate exit from or entry to the chair. The control console contains all of the switches required to operate the instrument in the various modes of operation, and those which control the various power inputs to the instrument components. In addition, various indicators are provided to indicate to the operator the actual position of the tracking instrument as it approaches the various limit stops, and lamps which indicate to him when the instrument has achieved the elevation or azimuth limit positions.

The operator's sighting scope is a 12-inch-diameter 50-power Cassegrain-type telescope having a focal length of 50 inches. The sighting scope is mounted directly to the elevation trunnion shafts of the telespectrograph, and is collimated with the optical line of sight of the tracking instrument. The eyepiece is located at an off-center position at the rear of the telescope, that may be rotated 360° about the center of the telescope to allow the operator to track with either his left eye or his right eye.

Telescope Assembly

The primary optical system of the telescope, figure 4, comprises an f/3 36-inch clear aperture Cassegrain-type configuration having a 288-inch focal length. It consists of a 36-inch pyrex primary paraboloid supported across its back by 18 pneumatic flexure supports, and around the paraboloid circumference by 12 similar pneumatic supports. The supports apply pressure to the primary mirror, depending upon the elevation angle of the optical axis. The secondary is a 12-inch-diameter pyrex hyperbola which is held in position by a four-vaned spider having adjustment capabilities. The secondary may be manually adjusted axially or radially, or tilted by both coarse and fine adjustments located behind the reflector. An adjustable 6-inch-diameter diagonal mirror, projecting approximately 10 inches forward of the primary vertex, deflects the incoming light rays up to the spectrograph assembly, mounted along with the other subassemblies, on the flat surface on top of the telescope.

Spectrograph Assembly

The spectrograph assembly is basically a Czerny-Turner optical system which is contained in a cast, rectangular housing located on top of the center section of the telescope. The assembly contains the K-mirror and K-mirror support, two 5- by 12-inch reflectors, one 4- by 10-inch reflector, a photomultiplier, and a 4-inch-square diffraction grating, which is the heart of the spectrograph. The basic diffraction grating utilizes a 600 lines/mm surface, blazed for the second order at 3600 angstroms. Diffraction gratings are also available having both 400 and 830 lines/mm. A 7-inch by 1/2-inch exit aperture slit is provided, at the rear right of the spectrograph housing, to allow projection on the film of the first-order spectrum from 4500 angstroms to 9000 angstroms, and the second-order spectrum from 2250 angstroms to 4500 angstroms. The range beyond 9 microns, the near infrared, is sampled by eight infrared detectors which receive the spectral image through a rotating chopper.

The zero order spectrum from the diffraction grating is reflected through the side mirror, one rear reflector, and a zero order folding mirror onto the photomultiplier pickup. The zero order output, which is monitored by the photomultiplier, is used to control the film drive rate. At low zero order levels, the camera film drive operates to advance the film in steps of 1/2 inch every 3 seconds. As the light intensity is increased on the photomultiplier, the film is driven at variable rates from 0.1 inch/second to 2 inches/second. The output of the photomultiplier, which is the zero order pickup, is also recorded on the tape recorder, located in the adjacent electronic control console. In addition to the spectral response recorded on the film, a second, preset and preexposed light intensity is also recorded on the film to serve as a reference. This is done prior to the mission.

A field stop viewing fixture is provided which is mounted to the top of the spectrograph housing. The fixture is normally spring-loaded in the up position, out of the optical path. For initial alinement and adjustment of the convergent field at the field stop plane, the viewing fixture is moved down so that a 45° mirror reflects the image of the field stop up into the eyepiece.

Figure 5 shows the optical path through the instrument. Incoming radiation is reflected from the 36-inch f/3 primary mirror (1) to a hyperboloidal secondary mirror (2) with a magnification of 8/3 to a diagonal mirror (3) which directs the optical path out of the telescope to the spectrograph. The K-mirror assembly (9 and 9A) is an image rotating system, and a field stop (10) with three angular fields of view is selected by rotating a turret. These fields are 30, 60, and 90 arc seconds.

Radiation emerging from the field stop (10) diverges to a mirror (4) of the spectrograph package, where it is rendered parallel and directed toward the diffraction grating (G). Grating (G) disperses the radiation and directs it as parallel bundles in varying directions depending on the wavelength variation and the angle of grating. In normal operation, visible radiation is directed toward mirror (5). The mirrored infrared radiation is directed toward mirror (4), and the zero order of the grating is directed toward mirror (6).

The visible radiation is focused by mirror (5), through a 7-inch by 1/2-inch aperture (7), onto the camera film plane. The mirrored infrared radiation is focused by mirror 4 onto eight infrared detectors, which may be positioned along the infrared focal plane (8). Mirror 6 directs the zero order radiation to mirror 5, which redirects the zero order radiation toward mirror 12, which forms an image in white light of the radiation on the surface of the photomultiplier (13). The output of the photomultiplier is also used in a servo loop to drive the automatic exposure control of the camera so that the exposure time of a particular region of film is dependent on the intensity of light received on the photomultiplier (13). In normal operation, using a 600 line/mm grating, the distribution of the various wavelengths of the detectors is as follows:

Radiation between 9000 and 4500 angstroms is directed by the grating (G) onto mirror 5 in the first order. Radiation between 4500 angstroms and 2250 angstroms is directed by the grating onto mirror 5 in the second order. Hence, in the region between 9000 angstroms and 2250 angstroms, there will be overlapping spectra at all wavelengths for which the film is sensitive to both first- and second-order radiation. Mirrored infrared radiation from 1.1 microns to 5.5 microns is directed by the grating onto mirror 4, to the extent that mechanical interference permits. A detector may be located to intercept any desired band within these limits.

The purpose of the K-mirror assembly (9 and 9A) is to allow for orientation of the distant object image on the field stop, so that an object which is bigger in one direction than the other, can be rotated to a position such that the small direction is made parallel to the direction of dispersion, thereby allowing for maximum spectrum resolution.

Pressure Control System

A novel feature of the telescope is the method supporting the primary mirror. The supports are rubber bellows pressurized by pneumatic controllers whose set points are controlled by sine and cosine potentiometers which sense the elevation angle of the telescope. In figure 6, the pressure in the six radial support bellows is proportional to the cosine of the elevation angle. The pressure in the 18 axial supports is proportional to the sine of the angle. The weight of the mirror, approximately 500 pounds, is supported completely by the pressurized bellows. The mirror is located and inertial forces are taken by a central mechanical clamp.

The pressure control system regulates the air pressure supply to the primary mirror support assembly and is located on top of the telespectrograph assembly. Two modified aqualungs serve as the air accumulators and storage tanks for the pressure control assembly. The air supply from the tanks is fed through a flexible cable wrapper arrangement, about the telespectrograph trunnion axis, to the pressure control housing on top of the telescope. The pressure control system provides two air supply outputs to the mirror cell manifold. One output controls the 18 air bellows located across the back of the primary mirror cell, and the other supply provides the air for the 12 bellows mounted about the circumference of the primary mirror cell.

When the telespectrograph assembly is in a horizontal position, the air supply to the lower circumferential bellows systems is fed a constant pressure to maintain the radial positioning of the mirror cell. As the telespectrograph is elevated toward 90°, the pressure is gradually reduced until it reaches zero pressure when the telespectrograph is at the 90° position. In this manner, an equal pressure is maintained across the entire circumference of the primary mirror cell. As the telespectrograph is depressed toward the 0° position, the pressure is gradually increased until the full pressure is applied to the lower circumferential bellows system when the spectrograph has reached the 0° elevation.

When the spectrograph is at 0° elevation, there is no pressure applied to the bellows systems about the rear of the mirror cell. However, as the telespectrograph is elevated toward the 90° zenith position, the full pressure is gradually applied across the rear of the primary mirror cell. In this manner, constant pressure and positioning of the mirror cell is maintained. As the spectorgraph instrument depresses down toward 0° elevation, the pressure is gradually decreased until it reaches zero pressure when the spectrograph is positioned at 0° elevation.

Camera Assembly

The camera assembly mounts adjacent to the rear right section of the spectrograph assembly, directly to the spectrograph assembly base plate. The aperture slit, which is located in front of the camera assembly focal plane, fits adjacent to a corresponding slit at the rear of the spectrograph assembly. A rubber bellows is mounted between the two adjacent slits to provide a light-tight seal, preventing any ambient light from entering the focal plane of the camera assembly. The camera assembly is designed to accommodate standard 9-inch-wide aerial film. A dark slide is provided which slides in front of the entrance aperture of the camera assembly to block off all incoming light to the film when the camera assembly is not in use. The dark slide also actuates a switch, which cuts off all system power to the camera assembly when the dark slide is in position. In this manner, the camera assembly cannot be operated until the dark slide is removed.

The real time encoding light system is also located within the camera assembly. This system projects range timing code data on the outer margins of the film as it passes the focal plane of the camera assembly.

Tracking Control

Control of the azimuth and elevation drive systems of the mount assembly is accomplished through four modes of operation. These are: the Aided Tracking Drive System, the Target Acquisition System (TAS), the Manual Positioning mode, and the Data Function Generator mode (DFG). Aided tracking is accomplished through use of the stiff stick control on the operator's control panel. By proper manipulation of his control, the operator cannot only vary the direction of instrument tracking, but can also control the velocity and the acceleration of both of the mount axes. In addition, the aided tracking mode is also used as an override control when the mount is being driven by either the external TAS system or by use of a data function generator.

The aided tracking circuitry is provided to give the operator the maximum possible dynamic control over the mount. Generally, an expression describing the motion of the mount increases in refinement as higher terms are added. That is, a displacement and a velocity term will, for certain application term, added to the total expression, gives a very accurate description of the motion, particularly when short-term transients are involved.

The system is built around three types of standard operational amplifiers: integrators, differentiators, and amplifiers of (-1) gain.

When the system is operating strictly in the aided tracking mode, the signal from the stiff stick is transformed into a compound signal consisting of positional or displacement term, a velocity term, an acceleration term, and an impulse term. The summed terms are fed to the servo amplifier controlling the hydraulic valves, which in turn control the hydraulic motors on the mount. A tachometer feedback signal is also introduced in the standard manner in order to stabilize the total input to the servo amplifiers.

In the actual tracking situation, the dominant factors in the short-term transient period are those of the highest order, that is, the impulse and acceleration terms. During the steady state, the lower order terms become dominant. Unlike conventional tracking instruments where the operator must keep the stick depressed in order to maintain a constant velocity, the aided tracking mode is based on the fact that the operator need only tap the stick to give incremental correction. The necessary velocity memory is established by means of an operational amplifier and its associated potentiometer.

The Target Acquisition System (TAS) is used when the mount is slaved to external range instrumentation such as radar. In this mode, the radar signal is first converted to polar coordinates, and then applied to the coarse and fine synchro control transformers on the mount. The output of these synchro control transformers are the coarse and fine error signals which are used to drive the mount. The DATA Function Generator (DFG) mode is used when an external function generator applies a tracking drive d-c signal to the two mount drive axes. As noted above, the aided tracking control can override both the Data Function Generator input and the Target Acquisition System external input.

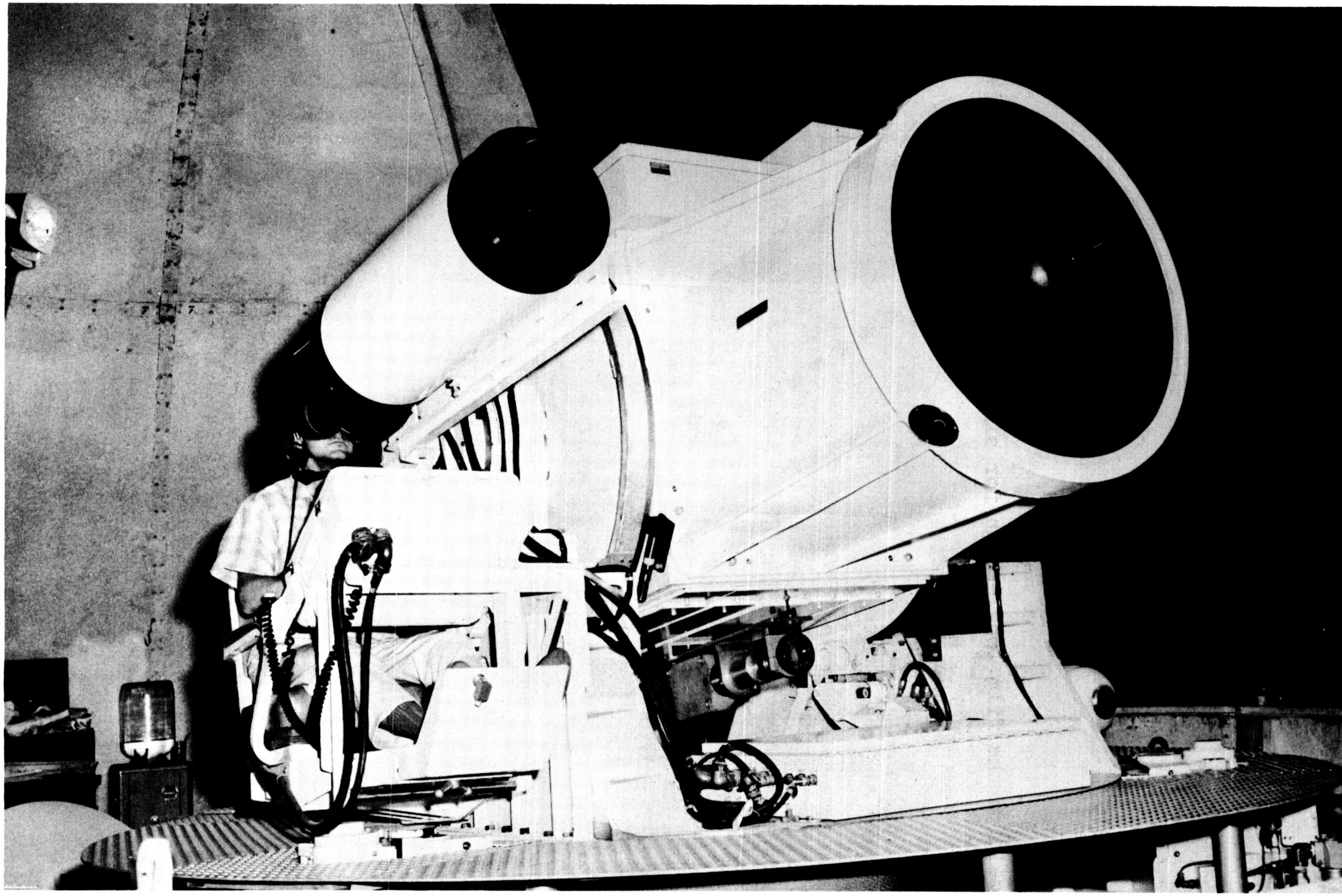
The manual mode is primarily a positioning mode in which the elevation and azimuth axes of the mount are positioned through use of the two positioning hand cranks on the operator's control panel. This operation utilizes a basic synchro positioning control system which is used for initial positioning of the azimuth and elevation axes of the instrument.

TEST RESULTS

As previously stated, the telespectrograph was built to be used for Project Fire support. At the end of a comparatively short test program at NOTS and Fecker Division, the TM mount and spectrograph were shipped separately to Ascension Island. Although the schedule was tight, it was decided to hold the spectrograph at Fecker for an additional month, while mount installation at Ascension was under way, to permit full aperture calibration. The spectrograph was then shipped to Ascension, mounted on the TIM, and calibrated. This operation was all the more remarkable considering that the two pieces had never been integrated and that this instrument represented a significant advance in the state of the art. To be specific, the mount was received at Ascension on January 29, the spectrograph on February 19, and the instrument was completed by March 4. This kind of operation was possible only because the same men who built the instrument went to Ascension and assembled it, and extremely good working relations existed between NOTS, Fecker, NASA, and range people.

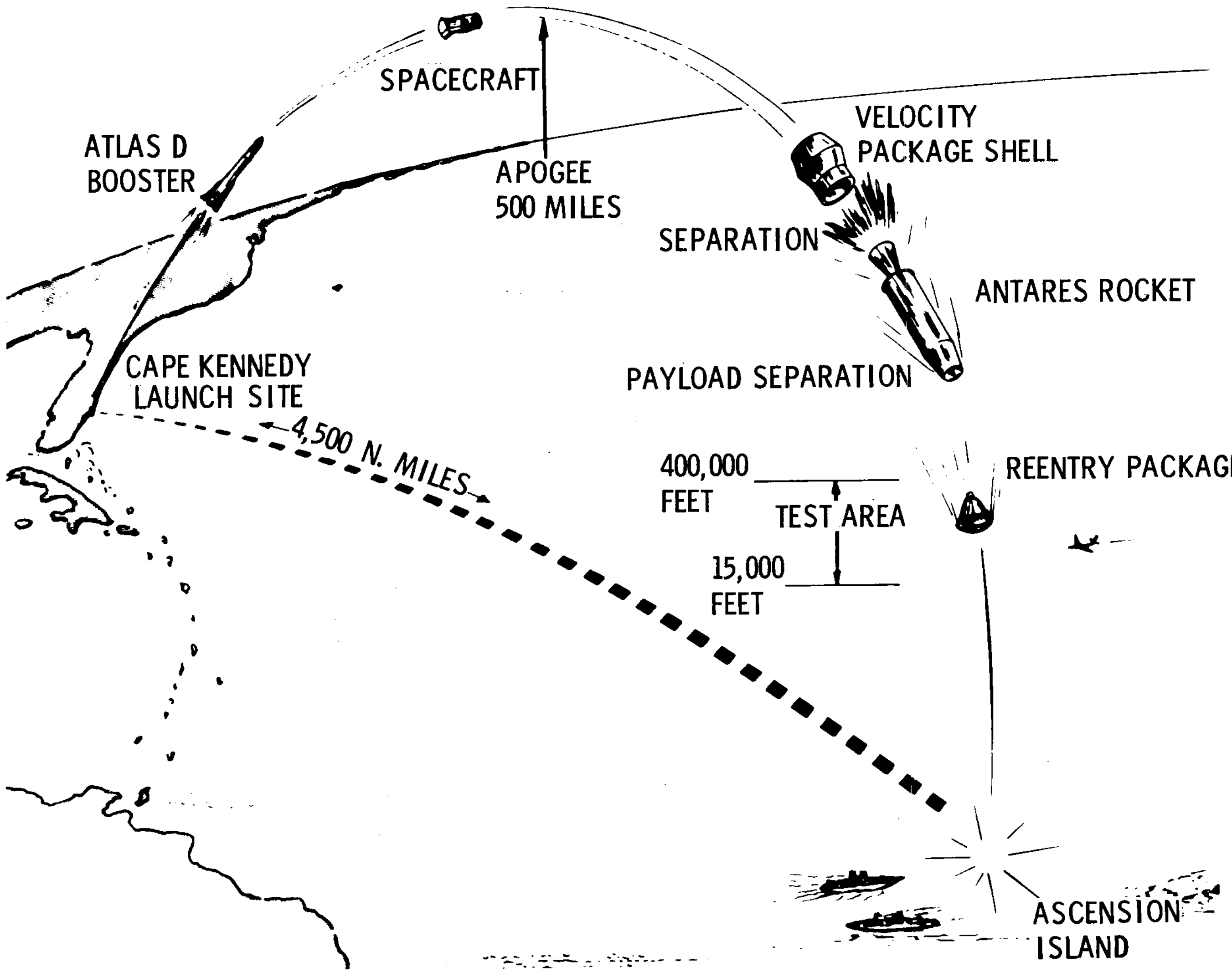
On completion of this assembly and calibration work, and the debugging one expects in an installation of this sort, extensive training and simulation tests were conducted, using an instrumented aircraft and targets of opportunity. Fortunately, it was possible to participate in five reentries before the Fire mission, although these reentries were not exact simulations of the Fire reentry. Figure 7 gives the results of these reentries and indicates the progress made during this time period. The last reentry before Fire yielded excellent data. This reentry was very bright and the operator reported no difficulty in tracking within the field of view of the instrument. On viewing the movie from the boresight camera, one can appreciate the tracking problems. The camera had a field of 1.2°, so that to assure data coverage the operator was required to keep the reentry glow in a circle of diameter about 1/100 the frame size.

The Fire reentry was the next night and the trajectory obtained was very close to nominal, with a maximum velocity of 37,891 fps attained. Acquisition by the telespectrograph was by the FPS-16 data link and difficulty was experienced by the operator in tracking throughout the reentry, which resulted in the image hitting the film 123 times out of a possible 476. In addition, the image did not remain on the film long enough for significant integration of the light energy, with the result that no spectra were obtained. Because of these low light levels, the 8 IR detector outputs were not usable, although they could possibly have been used had they not been lost in noise generated by wiring problems. A viewing of the movie of the boresight camera indicates these problems. Figure 8 gives the results of an analysis of the last two boresight camera films and shows the effects of the low light levels as they affected the ability of the operator to track.



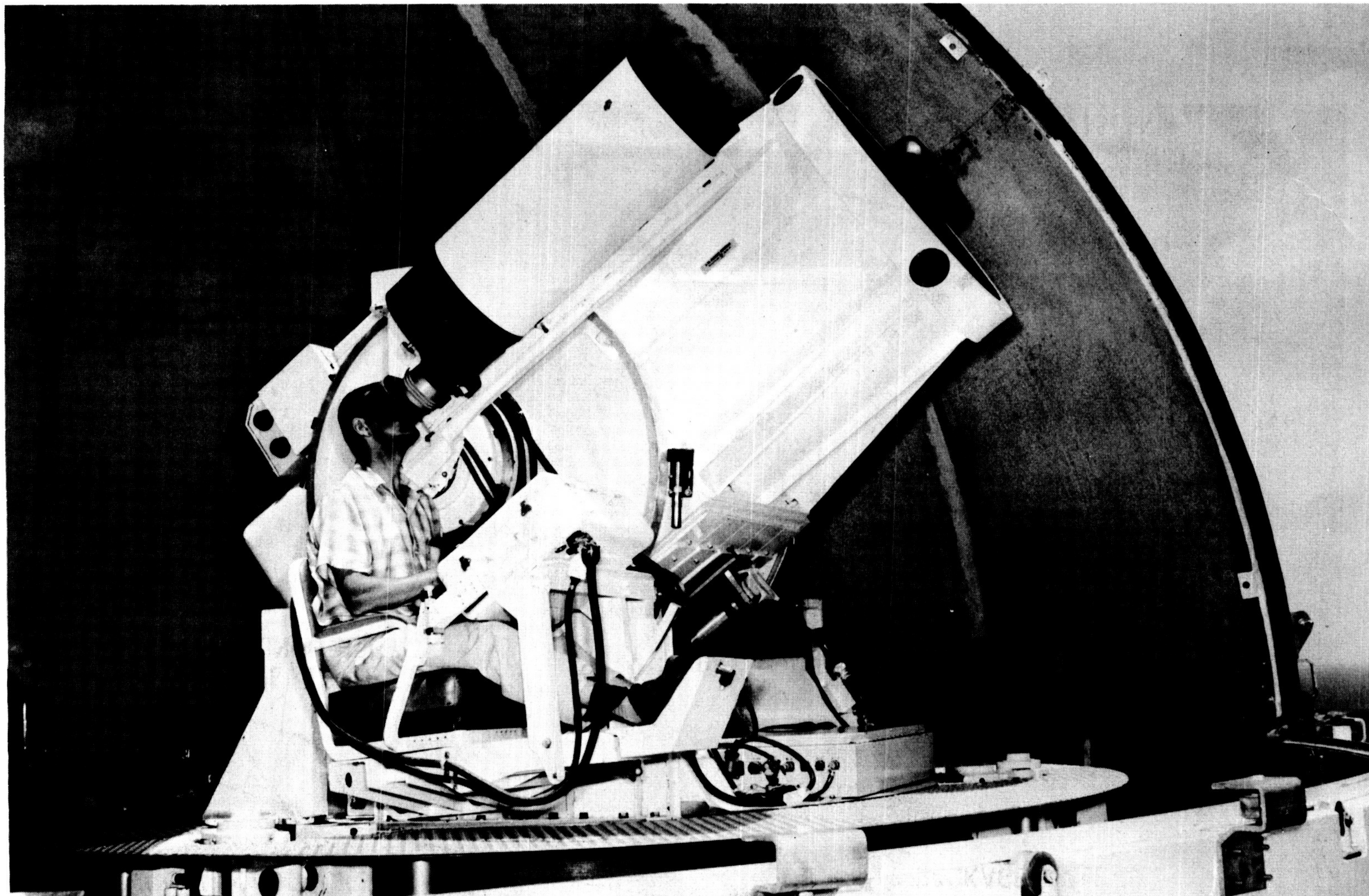
NASA

Figure 1.- Overall view of telespectrograph.



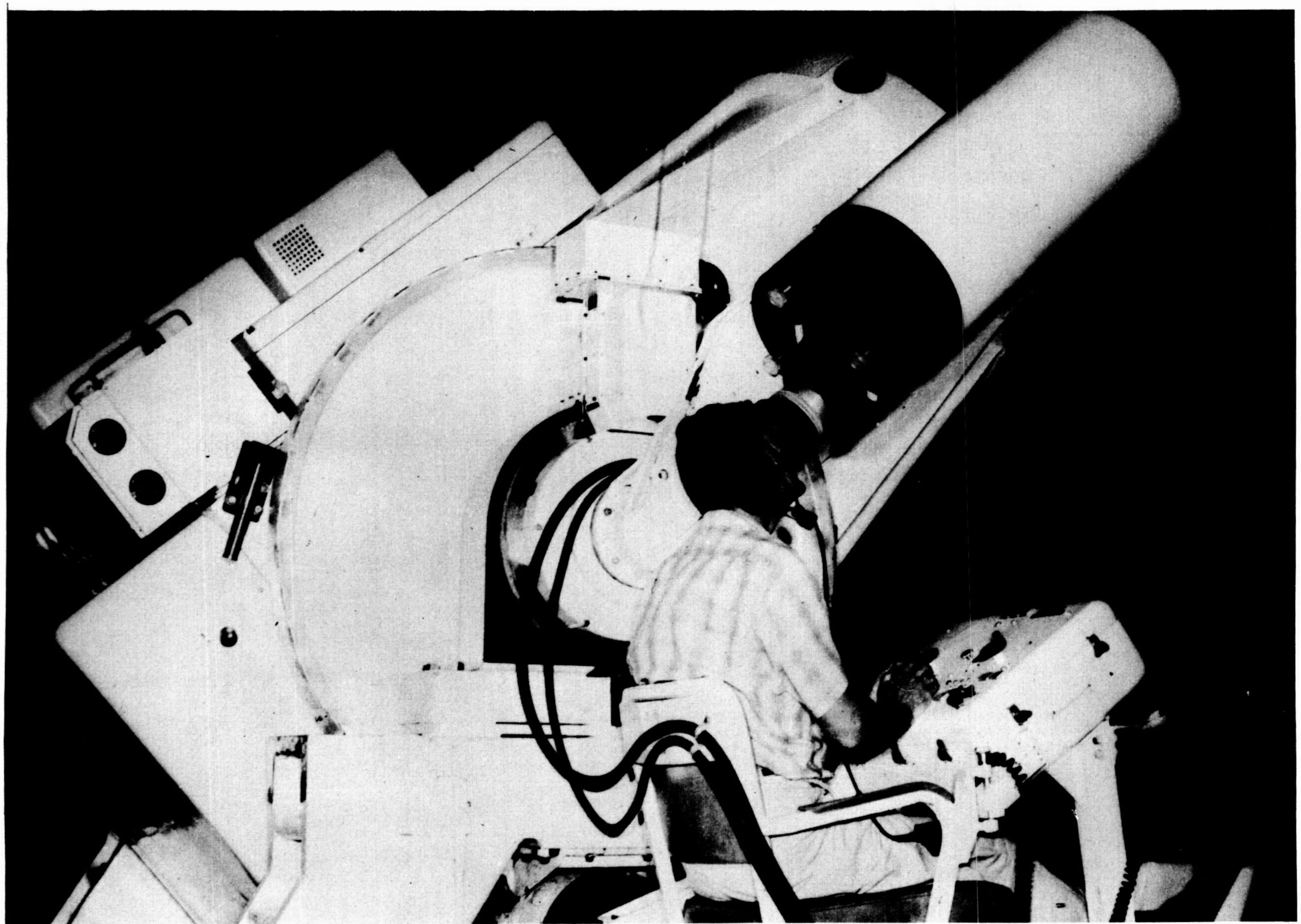
NASA

Figure 2.- Project fire trajectory.



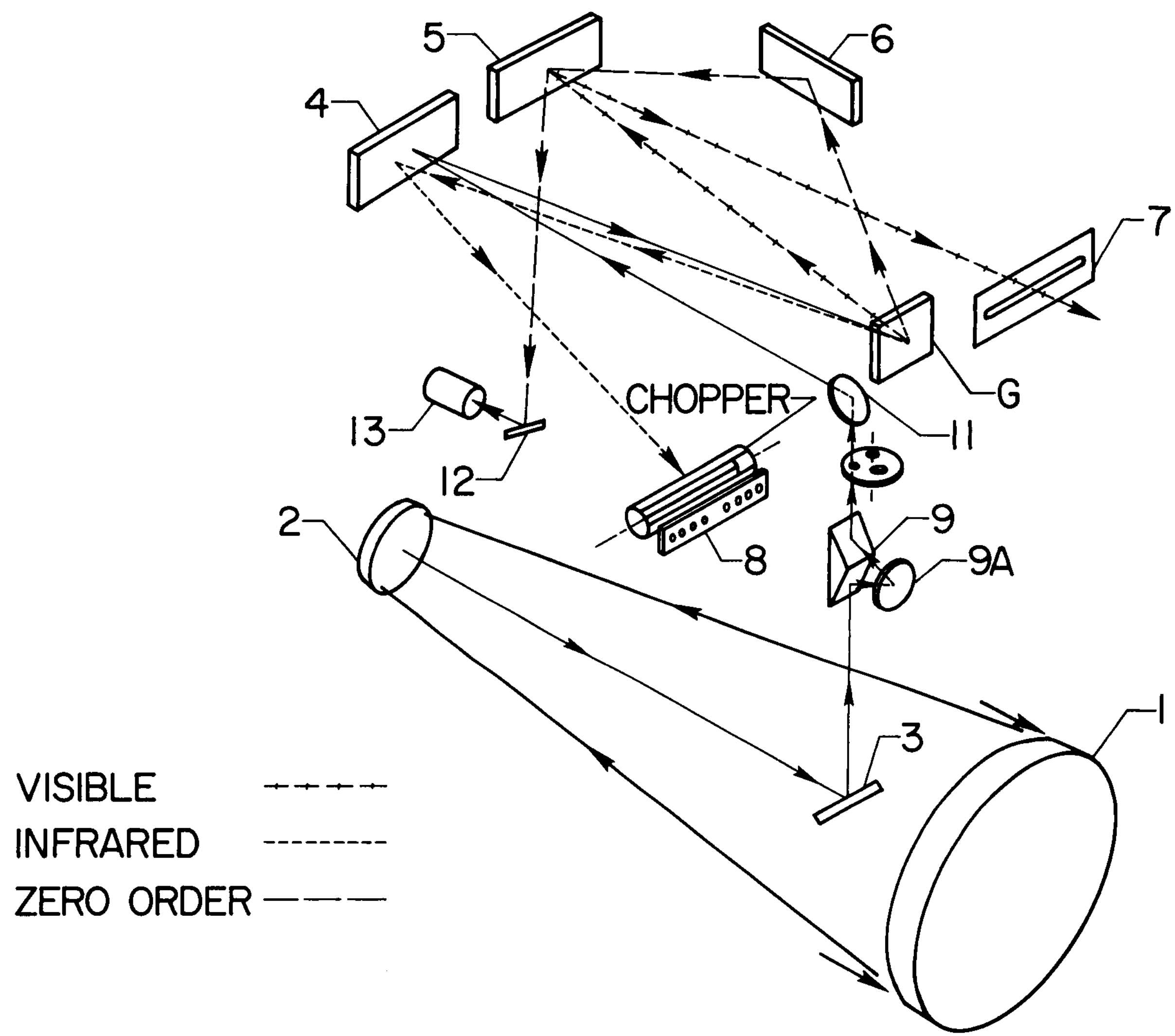
NASA

Figure 3.- Overall view of TIM.



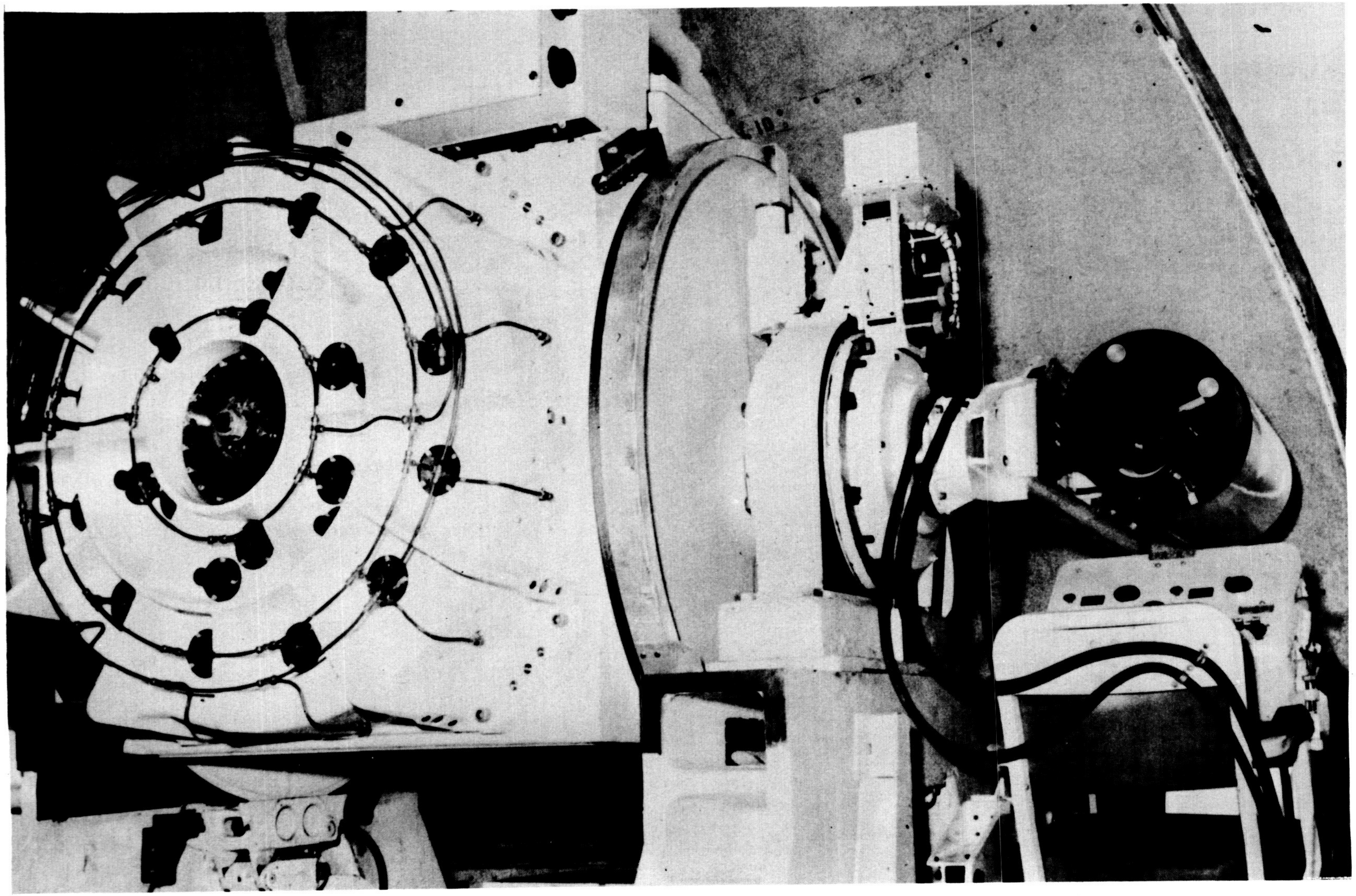
NASA

Figure 4.- Overall view of telescope and spectrograph.



NASA

Figure 5.- Schematic of optical path.



NASA

Figure 6.- Primary mirror support system.

TEST NUMBER	DATE	RESULTS
351	MARCH 13, 1964	DAYLIGHT SHOT, TRACKED REENTRY
50	MARCH 20, 1964	CABLE FAILURE
104	MARCH 23, 1964	TRACKED REENTRY, FILM OVEREXPOSED
57	MARCH 31, 1964	TRACKED REENTRY FILM UNDEREXPOSED
575	APRIL 1, 1964	RAIN
40	APRIL 8, 1964	CLOUD COVER
158	APRIL 9, 1964	TRACKED REENTRY, EXCELLENT SPECTRAL DATA
225	APRIL 14, 1964	PROJECT FIRE, TRACKED REENTRY, NO SPECTRAL DATA

NASA

Figure 7.- Telespectrograph tests.

	DATA POINTS		
TEST	EL	AZ	SIMULTANEOUS
158	134	56	39
225	9	47	2

NOTE: DATA POINTS FROM BORESIGHT CAMERA AT 12 FRAMES/SEC

NASA

Figure 8.- Comparison of tracking.

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